Measuring neutrino interactions with solar (and atmospheric) neutrinos

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Motivation: WHAT?

- At the moment, neutrino physics is in a truly unique position:
  - Lots of new, high quality data
    - Solid evidence for physics beyond the minimal SM
    - all implications are yet to be understood
- On the other hand, neutrino properties remain one of the least tested aspects of the SM
  - In particular, little is known about the interactions of the tau neutrino

Quantifying neutrino interactions

- Parameterize additional contributions due to heavy scalar/vector exchange as

$$L^{NSI} = -2\sqrt{2}G_F(\bar{\nu}_\alpha\gamma_\rho\nu_\beta)(\epsilon_{\alpha\beta}^{f\tilde{f}L}\bar{f}_L\gamma^\rho\tilde{f}_L + \epsilon_{\alpha\beta}^{f\tilde{f}R}\bar{f}_R\gamma^\rho\tilde{f}_R) + h.c.$$

- Well established only for the μ-neutrino

$$\epsilon_{e\mu} \lesssim 10^{-3},\ \epsilon_{\mu\mu} \lesssim 10^{-3} - 10^{-2}$$

- poorly known for the e-neutrino and <u>especially the τ-neutrino (not using SU(2))</u>

$$-0.4 < \epsilon_{ee}^{uuR} < 0.7,\ |\epsilon_{\tau e}^{uu}| < 0.5,\ |\epsilon_{\tau e}^{dd}| < 0.5,$$
$$|\epsilon_{\tau\tau}^{uuR}| < 3$$

S. Davidson et al, JHEP 0303, 011 (2003)

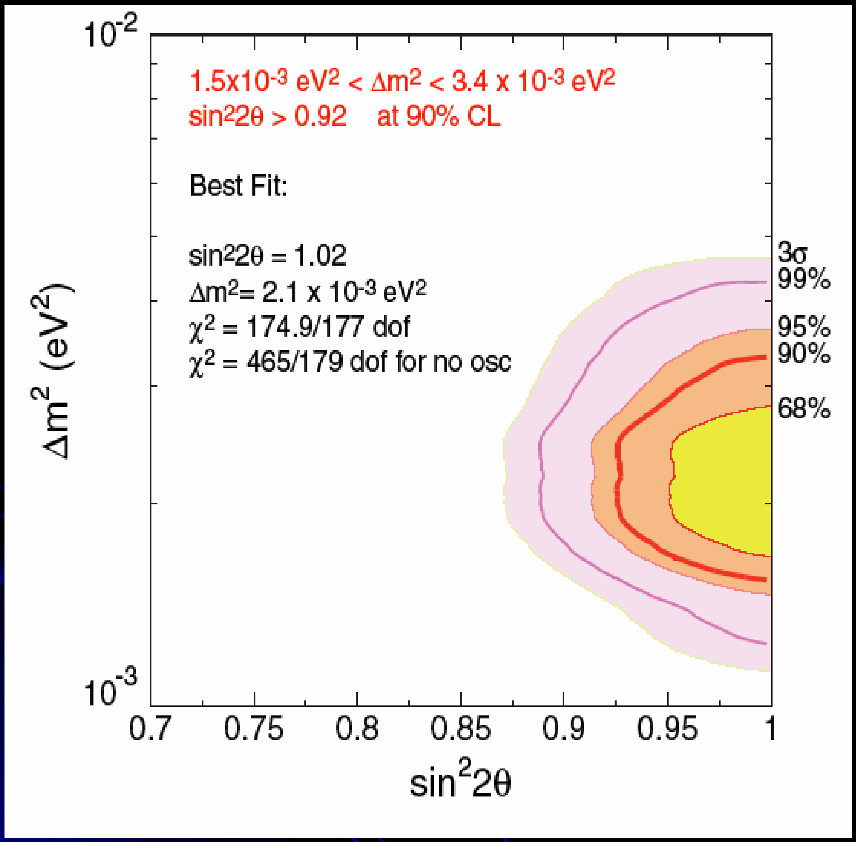
WHY solar and atm. neutrinos?

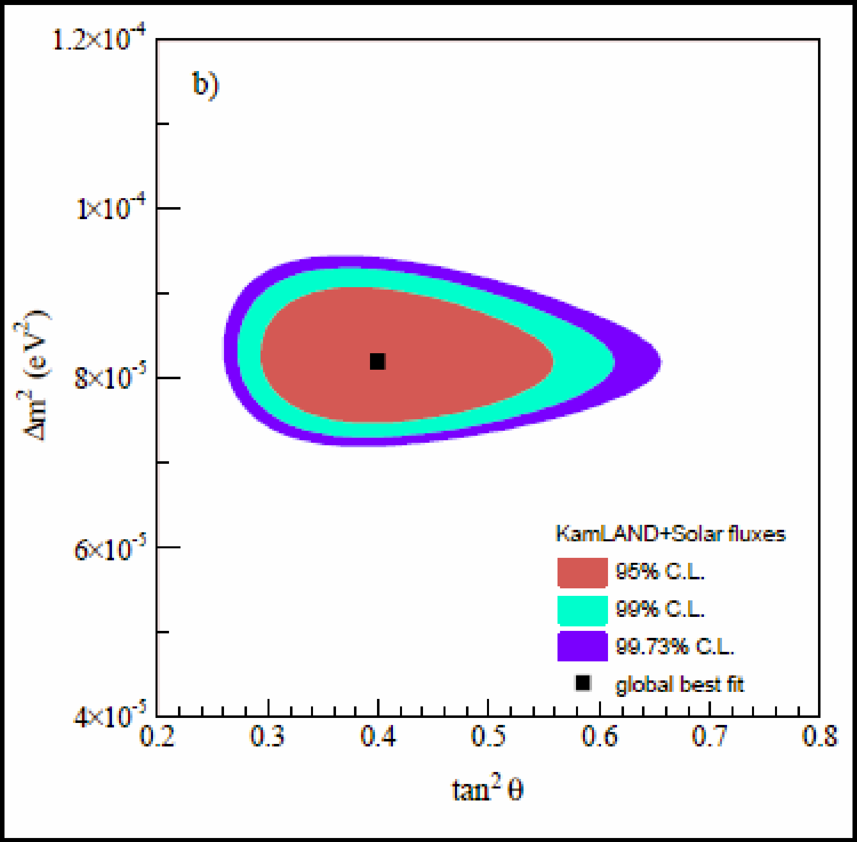
- Need a "ν_τ beam"!
  - Oscillations (both in solar and atmospheric neutrinos), make ν_τ's, according to the standard combined analysis
  - In the standard case, the oscillation parameters are quite well known by now

➢ Can we use these data to constrain neutrino interactions?

➢ Are oscillations robust? Do non-standard interactions (NSI) spoil this picture?

Oscillations: standard analysis





Robust? Can constrain NSI?

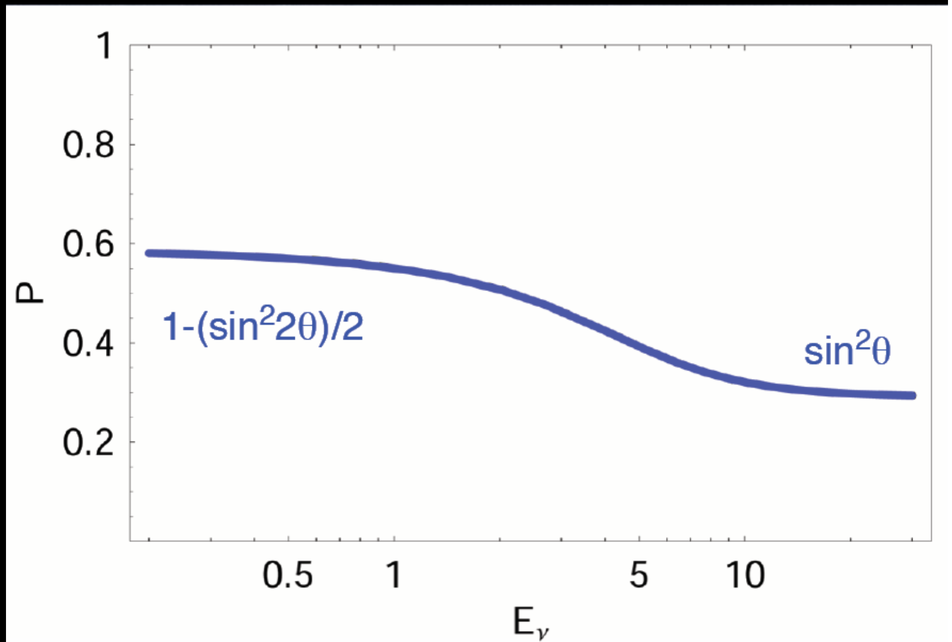
NSI and solar neutrinos: summary

- Solar neutrinos:
  - Constrain the NSI parameter space, beyond what is possible with accelerators
  - In the remaining part of the parameter space, the NSI effects can be completely non-trivial! Can give a new solution, LMA-0, $\rightarrow$ uncertainty in the determination of the osc. parameters.

Standard LMA solution: physics

- ^{8}B survival probability $\sim$ 30%, flat (SNO, Super-K)
- GALLIUM experiments (SAGE, GALLEX + GNO) see about 54% of the SSM prediction

> Δm^2 is chosen to match the density in the solar core, such that the high-E ν's undergo adiabatic conversion ($P_{ee}=\sin 2\theta$), while the low-E ones don't ($P_{ee}=1-\sin^2 2\theta/2$)

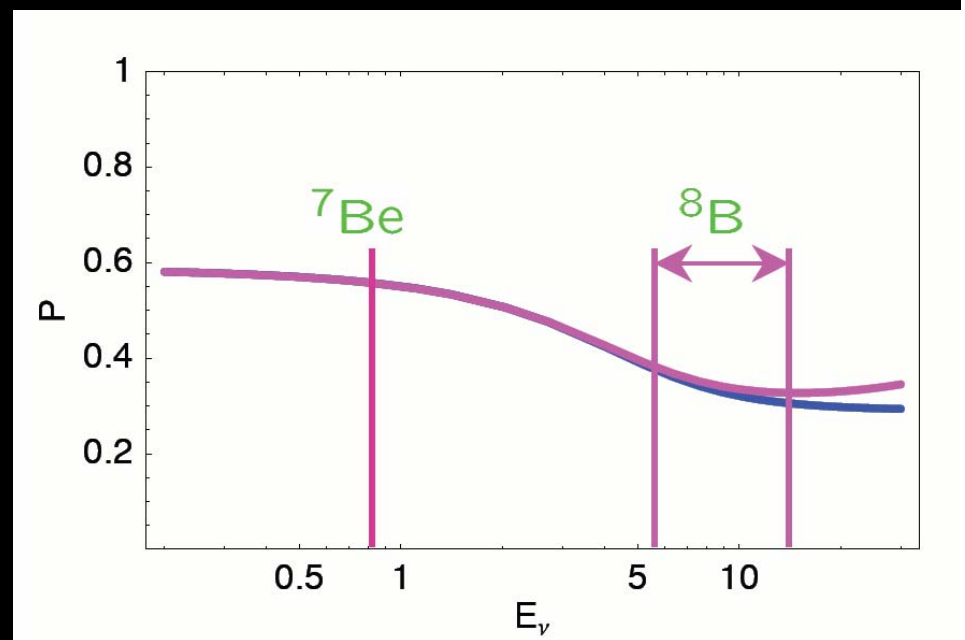


Standard LMA solution: physics

- For smaller $\Delta m^2/E$, will hit the resonance condition in the Earth

-> need to worry about the Earth regeneration effect

  - Put SNO and SK energies in the narrow "flat" window between the Earth and the solar resonances



Solar analysis: setup

- Take the matter term in the osc. Hamiltonian to have the form

$$H_{\text{mat}} = \sqrt{2} G_F n_e \begin{pmatrix} 1+\epsilon_{ee} & 0 & \epsilon_{e\tau}^* \\ 0 & 0 & 0 \\ \epsilon_{e\tau} & 0 & \epsilon_{\tau\tau} \end{pmatrix}.$$

$$\epsilon_{\alpha\beta} \equiv \sum_{f=u,d,e} \epsilon_{\alpha\beta}^{f} n_f / n_e$$

$$\epsilon_{\alpha\beta}^{f} \equiv \epsilon_{\alpha\beta}^{fL} + \epsilon_{\alpha\beta}^{fR}$$

- The solar problem reduces to a 2x2 ν_e-ν_μ' system

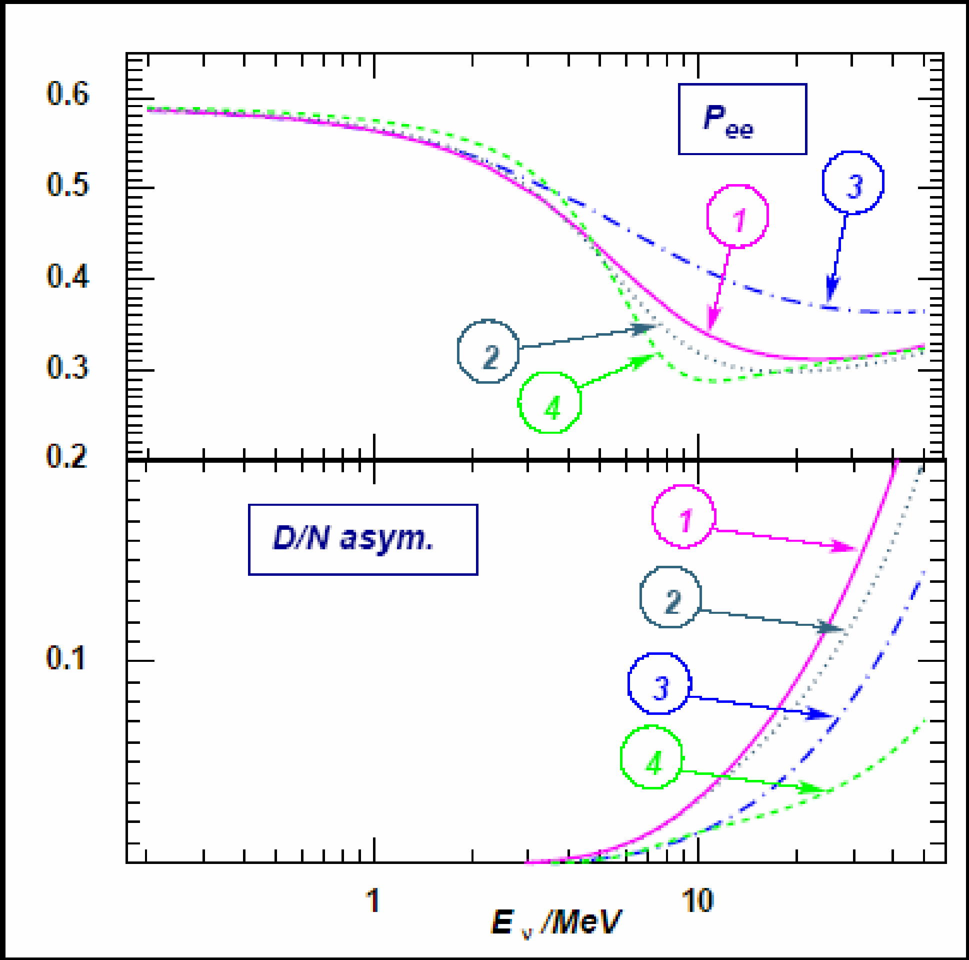
$$H_{\text{mat}}^{2\times 2} = \sqrt{2} G_F n_e \begin{pmatrix} 1+\epsilon_{ee} & -\epsilon_{e\tau}^* \sin\theta_{23} \\ -\epsilon_{e\tau} \sin\theta_{23} & \epsilon_{\tau\tau} \sin^2\theta_{23} \end{pmatrix}.$$

$$H_{\text{vac}} = \frac{\Delta m_\odot^2}{4E_\nu} \begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix}$$

Effect of the NSI on the solar survival probability and day/night asymmetry

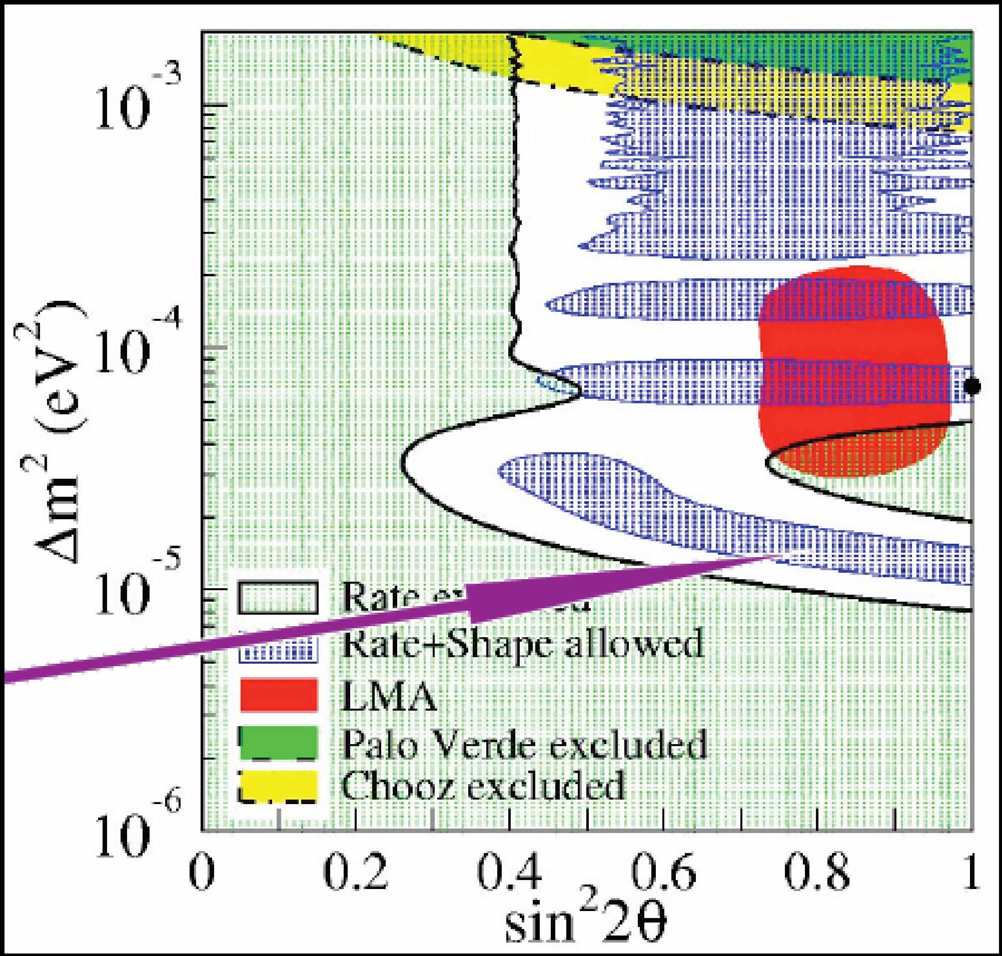
- Effect depends on the sign of $\varepsilon_{e\tau}$!

1. $\varepsilon_{11}^{u}=\varepsilon_{11}^{d}=\varepsilon_{12}^{u}=\varepsilon_{12}^{d}=0$
2. $\varepsilon_{11}^{u}=\varepsilon_{11}^{d}=-0.008$, $\varepsilon_{12}^{u}=\varepsilon_{12}^{d}=-0.06$;
3. $\varepsilon_{11}^{u}=\varepsilon_{11}^{d}=-0.044$, $\varepsilon_{12}^{u}=\varepsilon_{12}^{d}=0.14$;
4. $\varepsilon_{11}^{u}=\varepsilon_{11}^{d}=-0.044$, $\varepsilon_{12}^{u}=\varepsilon_{12}^{d}=-0.14$.



LMA=0: physics

- The d/n effect is proportional to $\sin(2\theta-2\alpha)$, where θ is the vacuum angle and α is the mixing in H_{mat}.
- When the d/n effect is suppressed, the allowed solar region extends to low Δm^2



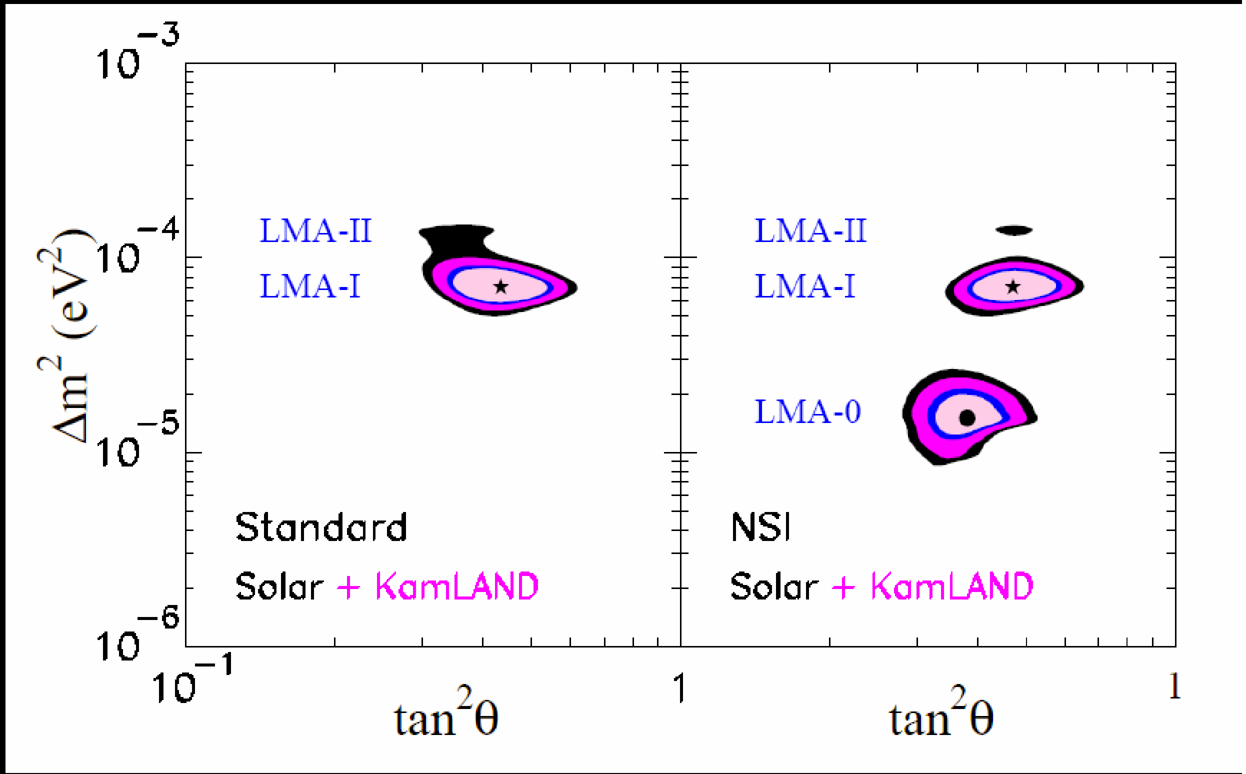
LMA-0: fit

- Choose a point that cancels the d/n effect:

$\varepsilon_{ee}^{d} = \varepsilon_{ee}^{u} = -0.025$,

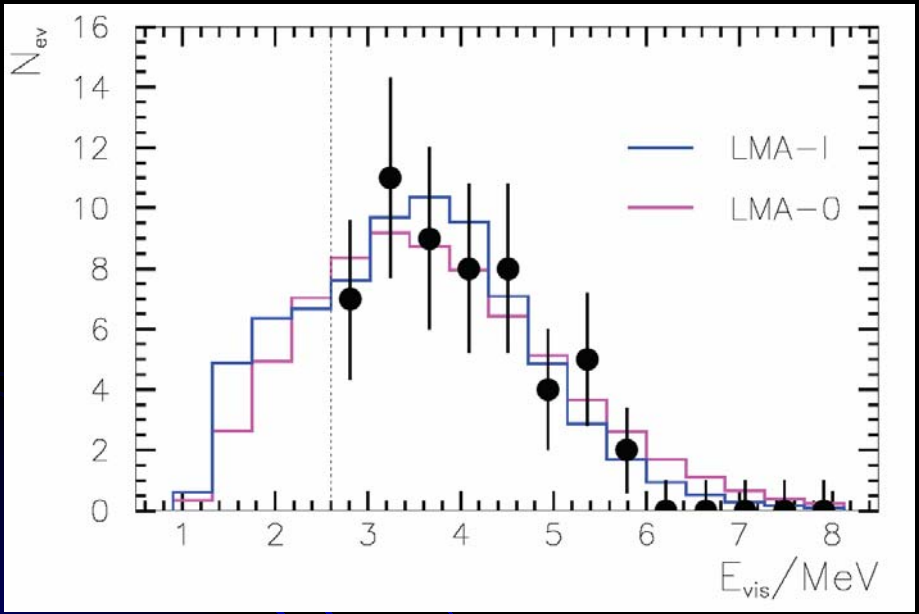
$\varepsilon_{e\tau}^{d} = \varepsilon_{e\tau}^{u} = 0.11$,

$\varepsilon_{\tau\tau}^{d} = \varepsilon_{\tau\tau}^{u} = 0.08$.

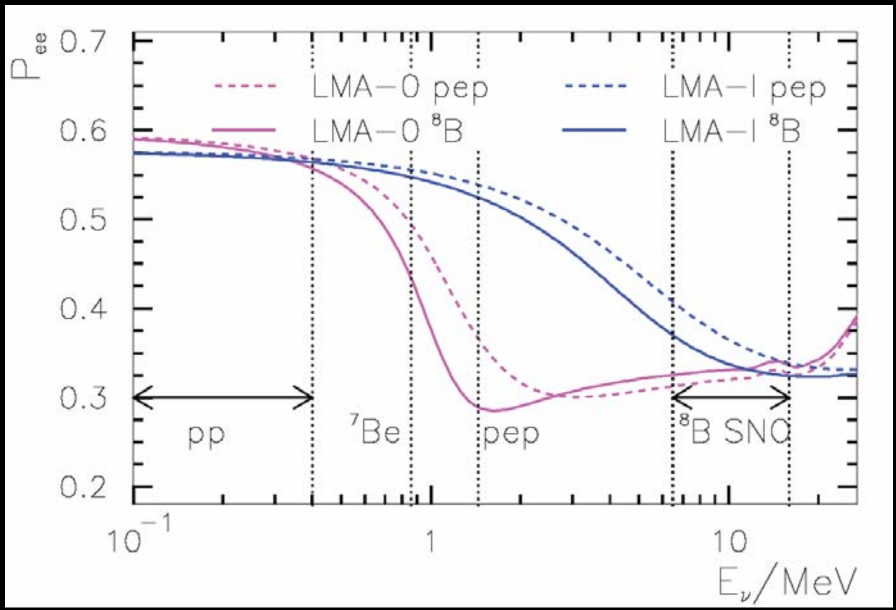


Testing LMA-0

KamLAND



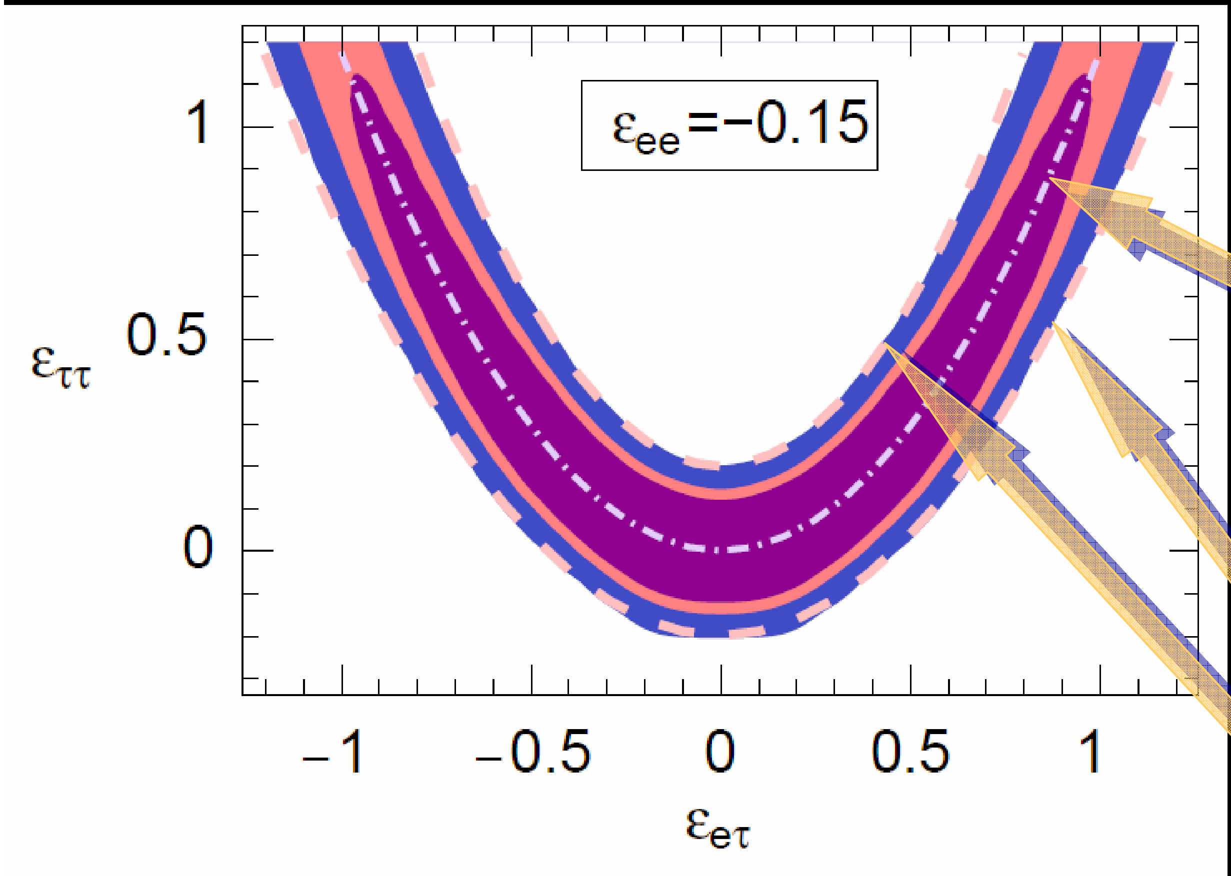
Solar neutrino experiments



Atmospheric neutrinos and NSI: background

- Earlier 2-family $\nu_\mu \leftrightarrow \nu_\tau$ analysis
  - very tight constraints on $\varepsilon_{\mu\tau}$, $\varepsilon_{\tau\tau}$
  - Do they extend to $\varepsilon_{e\tau}$? Rule out solar LMA-0?
- However, the atmospheric analysis DOES NOT reduce to a 2x2 ν_μ-ν_τ system!
  - Our 3-family analysis gives qualitatively new effects:
    - find bounds on NSI, but large NSI ($\varepsilon_{e\tau} \sim \varepsilon_{\tau\tau} \sim 1$) can be consistent with the data
    - The large NSI change the osc. fit: $\theta < \pi/4$, $\Delta m^2 \uparrow$

Allowed NSI range: fit and predictions



Scanned 4-D space ($\varepsilon_{e\tau}$, $\varepsilon_{\tau\tau}$, Δm^2, θ); marginalized over Δm^2, θ

$$\epsilon_{\tau\tau} = |\epsilon_{e\tau}|^2/(1+\epsilon_{ee})$$

$$|1+\epsilon_{ee}+\epsilon_{\tau\tau}-\sqrt{(1+\epsilon_{ee}-\epsilon_{\tau\tau})^2+4|\epsilon_{e\tau}|^2}| \lesssim 0.4.$$

Effect of NSI on the oscillation fit

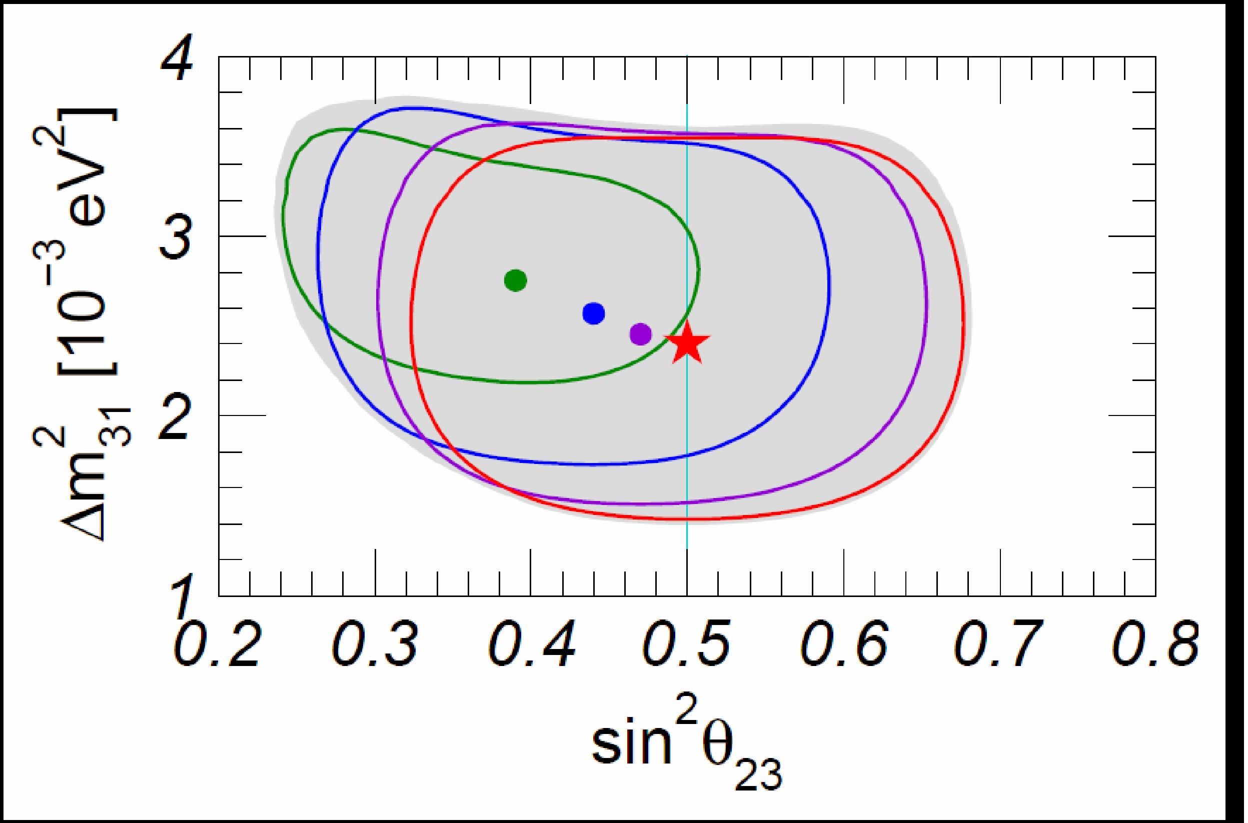
- The best-fit region shifts to smaller θ and larger Δm^2: $\cos 2\theta \simeq s_\beta^2/(1+c_\beta^2)$; $\Delta m^2 \simeq \Delta m_m^2(1+\cos^{-2}\beta)/2$

$\epsilon_{e\tau} = 0, \epsilon_{\tau\tau} = 0;$

$\epsilon_{e\tau} = 0.30, \epsilon_{\tau\tau} = 0.106;$

$\epsilon_{e\tau} = 0.60, \epsilon_{\tau\tau} = 0.424;$

$\epsilon_{e\tau} = 0.90, \epsilon_{\tau\tau} = 0.953.$



Testing the NSI

- SNO should lower its threshold to look for the upturn in P_{ee}
- Borexino should measure ^{7}Be line, to see if the flux is lower, as predicted by LMA-0
- Pep neutrinos!
- Atmospheric mixing angle should be probed by MINOS: will test the large NSI possibility
- NO-LOSE situation: confirmation of the standard scenario would place strong bounds on the NSI. In the opposite case, new physics at the 10^2-10^3 GeV!